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Evolutionary, multi-scale analysis of river bank line retreat using continuous wavelet transforms: Jamuna River, Bangladesh

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ABSTRACT

In this study continuous wavelet transforms are used to explore spatio-temporal patterns of multi-scale bank line retreat along a 204 km reach of the Jamuna River, Bangladesh. A sequence of eight bank line retreat series, derived from remotely-sensed imagery for the period 1987–1999, is transformed using the Morlet mother wavelet. Bank erosion is shown to operate at several characteristic spatial and temporal scales. Local erosion and bank line retreat are shown to occur in short, well defined reaches characterized by temporal persistence at the same location, and separated by relatively stable reaches. In contrast, evidence of downstream propagation of bank line retreat patterns is evident at larger spatial scales. The intensity of localised bank line retreat (i.e. at scales of 0–20 km) is strongly related to the magnitude of monsoonal peak discharge, but this relationship weakens as the spatial scale of erosion increases. The potential of continuous wavelet analysis for enhancing our understanding of morphological evolution in complex fluvial systems with multi-channel planforms is discussed.

1. Introduction

The planform evolution of the Jamuna River, Bangladesh, the distal portion of the Brahmaputra, has been the focus of many studies in which the aim has been to assess, characterize and quantify the magnitude and distribution of bank line migration (e.g. Coleman, 1969; Sarma and Basumallick, 1984; Singh et al., 1990; Thorne et al., 1993; Thorne and Russell, 1993; Halcrow, 1994; Goswami, 1995; Thorne et al., 1995; Goswami et al., 1999; Ashworth et al., 2000; CEGIS, 2000; Khan and Islam, 2003; Sarma and Phukan, 2004; Sankhua et al., 2005; Sarma, 2005; Sarma and Phukan, 2006; CEGIS, 2007; Takagi et al., 2007). However, quantification and prediction of the spatio-temporal patterns of bank line migration exhibited by the river are complicated by its large geographical scale (here synonymous with extent) and its complex planform, which features elements of meandering, braiding and anastomosing (Ferguson, 1993). The large geographical scale has thus far precluded the application of well-established hydraulic geometry relationships or process-based explanatory models due to the difficulties associated with up-scaling (Latrubesse, 2008). Furthermore, the river's complex and dynamic planform has also precluded application of conventional, geometric models developed for simpler, meandering channels (e.g. Ikeda et al., 1981; Parker et al., 1983; Johannesson and Parker, 1989; Zolezzi and Seminara, 2001; Camporeale et al., 2005). In fact, the difficulty inherent in large-scale, long-term studies of channel evolution and bank line migration in complex, multi-channel rivers prior to the wide availability of high definition, remotely sensed imagery explains why such studies have, until recently, been rarely conducted (Best and Bristow, 1993; Richardson, 1997). To date, the majority of geomorphological studies of the Jamuna have instead focused on investigating the processes responsible for channel evolution and bank line migration at the scale of the individual geomorphological unit. Examples include studies of channel bifurcations and braid bars (Ashworth et al., 2000; Richardson and Thorne, 2001); braid bars and associated floodplain embayments (Thorne et al., 1993; Halcrow, 1994) and the evolution of meander bends in major anabranches (Ellis, 1993; Thorne and Russell, 1993).

The bank line adjustment processes associated with these different geomorphological units exhibit non-stationarity (spatial and temporal localisation) as well as different, characteristic bank migration rates and scale-dependency in space (circa 10^2–10^4 m) and time (circa 10^0–10^1 yr). It follows that, in rivers with multi-channel planforms, the overall pattern of bank retreat is characterized as a complex non-stationary waveform within which multiple, characteristic erosion patterns co-exist at different scales, and at different downstream locations. For example, Thorne et al. (1993) identified a gross-scale control of planform evolution associated with island and nodal reaches first described by Coleman (1969) that are spaced along the channel at intervals of circa 30 km. They also identified local bank migration processes that are driven by braid bar growth and migration and which operate at smaller spatial (3–6 km) and

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over shorter temporal scales (2–5 years). Their findings contrast with those of Ellis (1993), who observed bank erosion and embayment formation related to meander growth and migration in near-bank anabranches that occur at spatial scales of hundreds of metres to several kilometres, persist over periods of 1–12 years, and drive erosion rates ranging from 50 to over 250 m yr^{-1}. More recently, CEGIS (2007) identified bank erosion and floodplain embayment forming processes associated with bar form development in the Jamuna river operating at spatial scales of 3–15 km, over periods of approximately 15 years and with erosion rates of the order of 200 m yr^{-1}. A finding common to these studies was that rates of downstream migration in the locations of severe bank erosion also appear to be scale-dependent. This is consistent with the downstream movement of sand bars (Coleman, 1969) and changes in the location of relatively stable and unstable reaches over time (Takagi et al., 2007), which all suggest a link to the downstream propagation of sediment waves (Gilbert, 1917; Madej and Ozaki, 1996; Wathen and Hoey, 1998). Indeed both Thorne et al. (1993) and Takagi et al. (2007) identified wave-like patterns of channel migration, with characteristic wavelengths of ~150 km and ~35 km, respectively. These findings suggest that the complex patterns of bank retreat observed in the Jamuna result from the superimposed and cumulative effects of spatially-transient bank erosion processes, operating semi-independently at a range of spatial and temporal scales.

Marcus and Fonstad (2010) argue that the development and availability of new remote sensing technologies, coupled with widening accessibility to GIS, have led to the emergence of the 'remote sensing of rivers' as a sub-discipline of fluvial geomorphology. Complex patterns of bank migration are now commonly investigated based on temporal sequences of bank line data, captured from aerial photographs or remotely-sensed imagery. These data are analysed within a geographical information system (GIS) so that rates of bank line retreat during specified periods can be computed (e.g. Gurnell et al., 1994; Mount et al., 2003; Mount and Louis, 2005; Swanson et al., 2011). In such studies, characterisation of downstream migration in bank erosion patterns reduces to a problem of localising in space the different magnitudes and scales of bank retreat events that can be discerned from the data, and evaluating how these localised patterns vary through time. In the past this has been achieved through a largely qualitative, visual appraisal of the patterns observed in sequential plots of bank position or change (e.g. Downward et al., 1994; Gurnell, 1997; Mount et al., 2003) coupled with examination of summary bank retreat statistics (e.g. CEGIS, 2000, 2007). Consequently, relatively little quantitative understanding of either trends in the spatial localisation associated with erosion at different scales or the relative rates of erosion driven by the different processes represented in the bank retreat record has been achieved. Moreover, it has been difficult to causally relate the observed patterns of bank retreat to likely geomorphological drivers; especially where these involve processes acting at different spatial and temporal scales. Commenting on this in a recent review, Kleinhans (2010) acknowledged the potential of remotely sensed time-series for unravelling channel pattern changes, but also observed that, 'we need quantifiers for subtle patterns to reveal structure objectively' (Kleinhans, 2010; page 313).

A more quantitative approach involves viewing the downstream distribution of bank retreat as a spatial signal of planimetric change. According to this approach, the different scales of erosion are equivalent to the different frequencies contained within the signal and their magnitudes are equivalent to signal amplitude. Accordingly, the downstream signal of erosion becomes the spatial equivalent of a standard time series signal, with distance substituted for time. When re-conceptualised in this way, techniques developed for the characterisation of frequency and amplitude in complex signals, become potentially powerful tools for characterising bank retreat. One common tool is the fast Fourier Transform (FFT), which offers good frequency localisation albeit at the expense of poor spatial localisation (Graps, 1995). However, the FFT requires the data series to be consistent with a statistically stationary model — something that cannot necessarily be assumed when analysing bank retreat sequences in river channels (Van Gerven and Hoitink, 2009). Alternative methods offering *both* frequency and spatial localisation, such as the windowed Fourier transform (WFT) (also known as the short-time Fourier transform) and wavelet analysis are therefore, preferable. Both have been applied to the analysis of river patterns (Ferguson, 1975; Camporeale et al., 2005; Van Gerven and Hoitink, 2009). However, the WFT is considerably less adaptable than wavelet analysis in that achieving good spatial resolution requires sacrificing frequency localisation, and *vice versa* (Fournier, 1995 page 11). As a result WFT was not selected for use in this research. While the use of wavelet analysis by geomorphologists remains rare, it has been widely used by hydrologists for the characterisation of runoff time series (e.g. Brillinger, 1994; Fraedrich et al., 1997; Labat et al., 1999; Compagnucci et al., 2000; Labat et al., 2000; Gaucherel, 2002; Labat et al., 2002; Lafreniere and Sharp, 2003; Coulibaly and Burn, 2004; Labat, 2005) Also, its potential in analysing signals in time series of river planform change has recently been recognised by Van Gerven and Hoitink (2009), who used it to characterize meander geometry on the Mahakam River, Indonesia. There are, however, no published examples of its use in characterising bank migration in large rivers with anabranching planforms.

In this paper we explore the potential of the continuous wavelet transform (CWT) for the quantitative characterisation of temporal sequences of downstream bank line migration patterns, using data recorded along a 204 km reach of the Jamuna River, Bangladesh. The CWTs presented in this paper quantify changes in bank position in the plane of maximum bank erosion. In line with previous studies of planform change from remotely-sensed data, this is assumed to be orthogonal to the downstream direction. This is believed to be the first time such an approach has been applied in a bank line retreat study. In Section 2 we describe the CWT method. Section 3 presents the geomorphologic application, results and interpretation of the CWT to patterns of bank line retreat on the Jamuna River. The key findings from the study are summarised in Section 4.

2. Methodology

Wavelet analysis comprises several mathematical transforms from which temporal (or spatial) series can be transformed into a 2-D time (or space)-frequency representation. A detailed treatment of the mathematics of wavelet transforms is beyond the scope of this paper, but may be found in publications covering both wavelet analysis theory (see Daubechies, 1992) and software implementation (Nason, 2008). In this paper we make use of the continuous wavelet transform (CWT) popularised by Torrence and Campo (1998). Our description of the CWT below draws from Torrence and Campo (1998) using the notation and development of Sadowsky (1996), Kumar and Foufoula-Georgiou (1997), and Biswas and Si (2011). In this description, $y(x)$ denotes the spatial series of left-hand bank (LHB) downstream distance measurements. We can define the CWT, which we denote by $W(s,\sigma)$, as the complex conjugation of $y(x)$ with a dilated and translated 'mother' wavelet function $\psi_{s,\sigma}(x)$:

$$W(s,\sigma)=\int_{-\infty}^{\infty}y(x)\overline{\psi_{s,\sigma}}(x)d(x) \tag{1}$$

where

$$\psi_{s,\sigma}(x)=\frac{1}{\sqrt{s}}\psi\left(\frac{x-\sigma}{s}\right). \tag{2}$$

Here, s represents the dilation (scale) of the wavelet function and σ represents the degree of distance translation along the series. The term $1/\sqrt{s}$ normalises the wavelet function energy at each scale (Kumar and Foufoula-Georgiou, 1997; Torrence and Campo, 1998). Eq. (2) emphasises that the wavelet function is in fact a 'basis' function (Fournier, 1995). For the CWT of a discretely sampled spatial series denoted by